DEMONSTRATION OF A LOW COST CRYOCOOLER ON A LONG DURATION BALLOON MISSION

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ABSTRACT

NASA/GSFC has been evaluating the use of low cost Stirling cycle cryocoolers for aerospace applications since 1994. These include the M77B and M77C cryocoolers built by Sunpower Corporation. To date NASA has tested eight M77B and two M77C cryocoolers, with 8 additional M77C units now under construction. The intent of this work is to determine the flight worthiness of these cryocoolers. The Sunpower M77 coolers are candidate for use on the Ultra Long Duration Balloons presently under development by NASA. The flight on the Long Duration Balloon (LDB) in July 1998 represented an opportunity to test the cryocooler in the high altitude balloon environment in order to gain experience to prepare for possible opportunities on the Ultra Long Duration Balloon (ULDB) missions. The Long Duration Balloon is typically a 10 to 15 day mission. Typical ULDB missions might be as long as 100 days or more, and it is this duration which now forces many science groups to consider the use of cryocoolers in place of stored cryogens. This paper will present the basic design of the cryocooler experiment, and data acquired during the flight. The paper will also include a general perspective on the use of cryocoolers on future ULDB flights.

INTRODUCTION

NASA Goddard Space Flight Center has been involved in the development of long life space-based cryogenic coolers for several decades. In recent years Goddard has been cooperating with aerospace and commercial companies to facilitate the commercialization of cryocoolers that can also be used in space. In addition to providing a service to US industry, Goddard's goal is to develop coolers that can meet the requirements of both space-based missions and ground-based applications. This dual use provides advantages to

NASA. Specifically, the coolers will have lower production costs because of the increased production rate and will be readily available. Also, once production rates have increased, the fabrication processes will become more uniform from cooler to cooler. Over time, this uniformity will improve reliability since variations from cooler to cooler can result in subtle defects that may limit the cooler lifetime.

The development of "dual use" cryogenic coolers is an example of NASA's drive to find ways to carry out scientific missions in a faster, better and cheaper manner. The use of balloon-borne instruments instead of space-based instruments is another example of NASA's push to reduce costs. Some scientific investigations can be carried out on high altitude balloons that are above most of the atmosphere. Examples include cosmic ray studies and certain X-ray studies. To facilitate these investigations, NASA has embarked on a program to extend the duration of high altitude balloon experiments. These programs include the Long Duration Balloon Program (LDB) and the Ultra-Long Balloon Program (ULDB).

NASA SCIENTIFIC BALLOON PROGRAM

The NASA ULDB Program at Wallops Flight Facility is developing a new super pressure balloon capable of sustaining a 1000 kg. science payload at an altitude of 35,000 meters for 100 days duration. The first full scale demonstration of this balloon will be an engineering test flight from Alice Springs, Australia in December 2000. The first experiment to fly on this vehicle is scheduled for December 2001. Although this experiment does not require cryogenics for their detector, future ULDB flights will. Four candidates for early ULDB flights require long duration cryogenic cooling. The Sunpower Stirling cycle cryocooler is a candidate to fill this anticipated requirement in future flights.

A Long Duration Balloon flight “flight of opportunity” was performed from Fairbanks in 1998. This flight provided an opportunity to expose the Sunpower Stirling cycle cryocooler to a long duration balloon environment. This was a combined effort between the Balloon Program at Wallops, the Cryogenics Branch at NASA / Goddard Space Flight Center, and the National Scientific Balloon Facility in Palestine, Texas.

DESIGN OF CRYOCOOLER EXPERIMENT ON LDB MISSION

Objective

The primary objectives for this mission were to determine the effectiveness of the passive radiator at removing heat from the cryocooler, to characterize the cryocooler’s thermodynamic performance, and to confirm mechanical and electromagnetic compatibility with other systems on the balloon.

Radiator Design

The Sunpower M77 Stirling cycle cryocooler dissipates approximately 100 watts of heat when running at maximum power. To dispel this heat, a passive radiator consisting of a flat aluminum plate, pointed at cold space, was used. The radiator was oriented away from the sun by rotating the gondola using a sun tracking motorized rotator in the flight train. In order to reject the 100 watts of heat generated by the cryogenic cooler while maintaining it under its maximum operating temperature limit, the passive radiator thermal design maximized conduction from its heat source to the radiator surface and radiation from the radiator surface to cold radiation sinks such as deep space (-273 deg C), earth (-18.7 deg C) and the balloon (variable). Also, the radiator design minimized the solar flux on the radiator surface and the view factors to other relatively warm balloon/payload system components. To accomplish this, the design of the radiator surface called for it to be inclined 55 degrees from the horizontal, located on the anti-sun edge of the payload with the radiator surface pointed in the anti-sun direction. The radiator surface was coated with Sherwin Williams A6W40 Super White paint (alpha=0.236, epsilon=0.895) to maximize the infrared radiation and minimize the solar absorption. The computed view factors, calculated with a Monte Carlo ray tracing technique, from the radiator surface to other sources/sinks for this configuration were: 0.667 to space, 0.136 to earth, 0.099 to the balloon, 0.085 to the other science components, 0.007 to the rotator assembly, cables and rigging, and 0.005 to the photo-voltaic panels. Under hot-case conditions, this radiator design resulted in a maximum predicted radiator temperature of +60 deg C. Under cold-case conditions, the radiator temperature was predicted to be +25 deg C.

Cryocooler Interface Issues

The cryocooler cold finger was enclosed in a vacuum bonnet and instrumented with a LakeShore DT-400 series temperature sensor and a resistive heating element to simulate the detector load.

Ground testing prior to flight included numerous tests to ensure that the cryocooler did not interfere with other scientific payloads on the balloon gondola. Of particular concern was a liquid nitrogen cooled germanium X-ray detector. Given the disparity between the cooler's input power and the energy detected by the detector, there are many potential sources for noise coupling. Among them are electromagnetic interference and microphonics. Microphonic noise is the electronic signals induced by mechanical vibrations stemming from the operation of the cooler. One goal of the experiment was to evaluate the signal degradation at the detector caused by EMI and vibration from the cryocooler.

The germanium radiation detector was located about half a meter from the mechanical cooler. The test consisted of an evaluation of the noise performance as the cryocooler power level was stepped up. At no time was there any indication that the cooler was interfering with the detector. This demonstrates the feasibility of using a mechanically cooled detector on a long duration balloon mission.

Control Electronics

The electronics developed for the cryocooler experiment had to be kept very small and have minimal complexity to meet the schedule dictated by this rapid deployment mission. The circuit design was based on electronics developed for use with Sunpower cryocoolers in the NASA/GSFC laboratory.

The basic electrical system diagram is shown in Figure 1. The power was supplied from solar panels, charge converter and batteries provided by the balloon gondola electrical system. The power system could provide 28 V dc power to the cryocooler experiment for the duration of the flight. The power input to the cryocooler system was fused at 10 amps.

The input commands for control of the cryocooler was performed through 4 latching relays. Power on / off, cooler start / stop, hi / low power, and hi / low heat load. The hi power level was set to about 87 watts, and the low power was set to about 78 watts. Hi heat load was 4 watts, and low heat load was 2 watts.

The cryocooler data file, which was included in the telemetry stream every 30 seconds, would provide radiator temperature, cooler heat sink temperatures, cold tip temperature, heat load voltage (indicating which load was on) and the cryocooler system bus current.

The cryocooler compressor motor was driven using a 28 V PWM servo amplifier, Model 4122Z made by Copley Controls. These amplifiers can deliver 10 amps continuous and 20 amps peak current. The balancer motor was also driven from the same amplifier but through a simple phase shift network which sets up the proper amplitude and phase relative to the compressor such that the vibration would be reduced. The proper relationship of phase and amplitude is primarily a function of cold tip temperature and was obtained from previous charcterizations of this cryocooler. The vibration being generated during the flight was not quantified, but it was determined to be at a level low enough to not interfere with other systems on the balloon gondola.

The function of the gain control network was to vary the amplitude of the sinewave drive signal. This closed loop circuit would read the cold tip temperature and adjust the signal level accordingly. The compressor power level would only increase if the cooler cold tip was getting colder. The purpose of this is to ensure that the free displacer piston is not overdriven. When the helium is warm there is insufficient damping of the displacer piston to allow full power to be commanded.

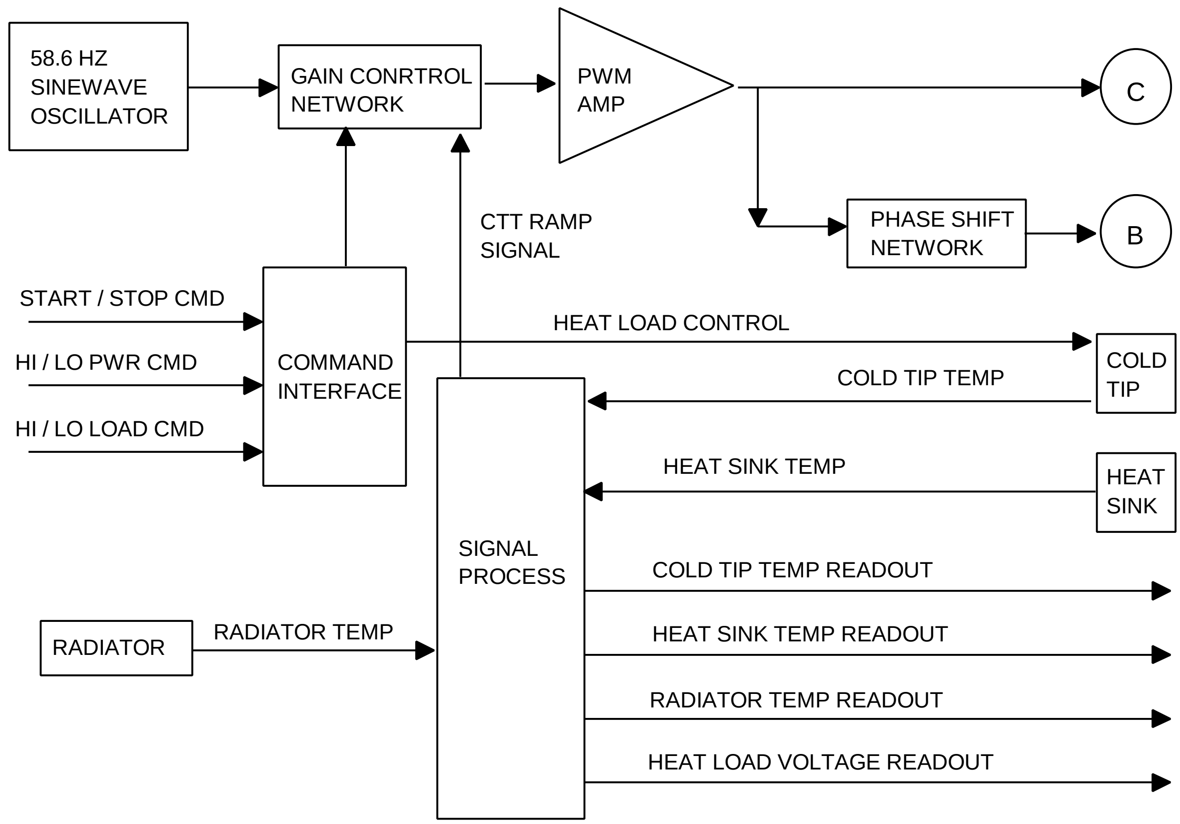

Figure 1: Block diagram of cryocooler control electronics

FLIGHT DATA

The first flight of the balloon was aborted after about 7 hours into the flight. The balloon only achieved about 100,000 feet altitude, rather than the 120,000 ft required. The balloon was recovered, and launched again some 10 days later. Although the first flight was short, sufficient data was acquired to evaluate cooler performance at one power level and one heat load. Figure 2 illustrates the performance of the radiator and heat sink for the cryocooler while on the runway, with the cooler running, during the ascent phase, and at altitude before the abort was commanded. The cryocooler was in low power mode for all of flight 1. The cold tip temperature as a function of compressor power for the first flight is presented in Figure 3.

A problem with the electronics, which was not realized prior to flight, was that the gain control network was temperature sensitive. As the heat sink temperature increased, the compressor power would increase. Figure 3 includes data collected on runway through abort. A power level change of about 10 watts per 40 degrees Celsius change in heat sink temperature was occurring.

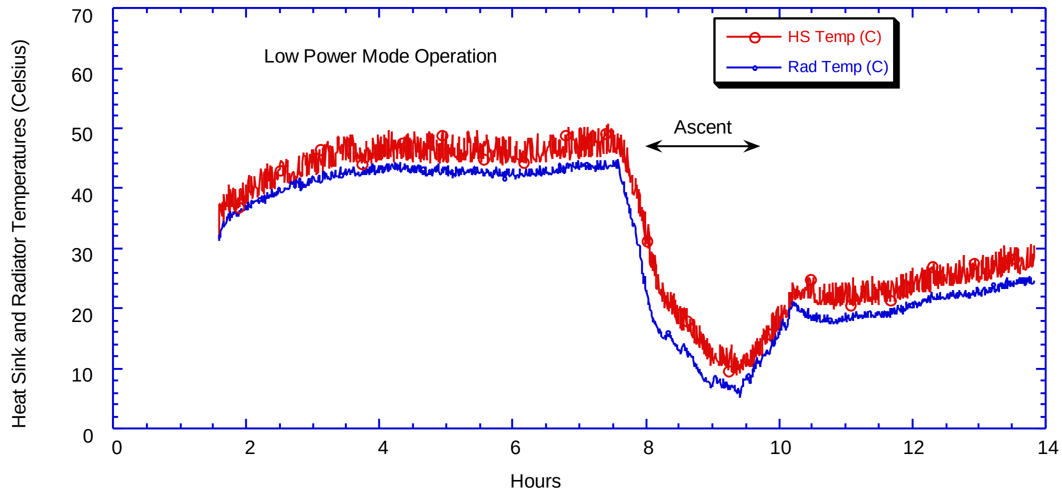

Figure 2: Heat sink and Radiator temperatures during the first flight

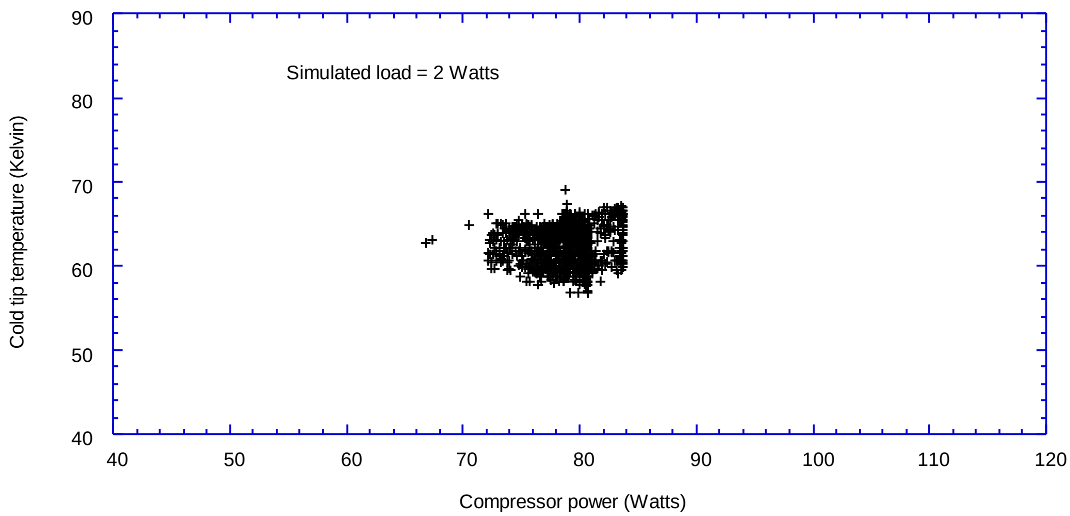

Figure 3: Cold tip temperature performance for the first flight

Flight 2 lasted 13 days. Data was collected with the cooler at low power and with low load, high power and with low load, and with the cooler off, with a 45 Watt heat load on the radiator. Unfortunately, data was not obtained for high power and high load, because the cryocooler compressor fuse blew sometime after the cooler was commanded to high power. This was due to the electronic gain control problem mentioned earlier, which resulted in excessive power.

A communication blackout with TDRSS occurred at 47 hours into the flight. The cryocooler was commanded to high power mode about 6 hours prior to the blackout. The compressor motor fuse blew sometime during the 10-hour blackout. When communications returned, the cryocooler was not running. Data analysis revealed that the cooler was still in low power mode, at that point the system was commanded to cooler stop mode, which automatically turned on the main 45 watt heater on the radiator. This permitted continued data collection of heat sink and radiator temperatures for the remainder of the flight with a fixed 45 watt heat load on the heat sink. The data link, however, continued to periodically blackout for the remainder of the flight.

Figure 4 shows the time base performance of cold tip and heat sink temperatures of the cryocooler while on the runway, through the ascent phase, and at altitude up to the point at which all data communications were lost. Notice the periodic nature of the heat sink temperature. Figure 5 illustrates the radiator and heat sink temperatures for the three power levels for the entire 13 day flight. Constant power operation of a cryocooler will result in a cold tip temperature which will vary as the heat sink temperature varies. On this flight, since the compressor power level was increasing as the heat sink temperature increased, the cold tip temperature remained relatively flat.

The cyclic nature of the radiator and heat sink temperature is primarily due to the day / night cycle, and was compounded by the power fluctuation problem. Constant cold tip temperature operation will most likely be the requirement for a cryocooler cooling a detector on a balloon flight. On future missions, either a robust controller will be required to maintain a constant cold tip temperature under such conditions, or some technique for keeping the radiator temperature more constant will be required.

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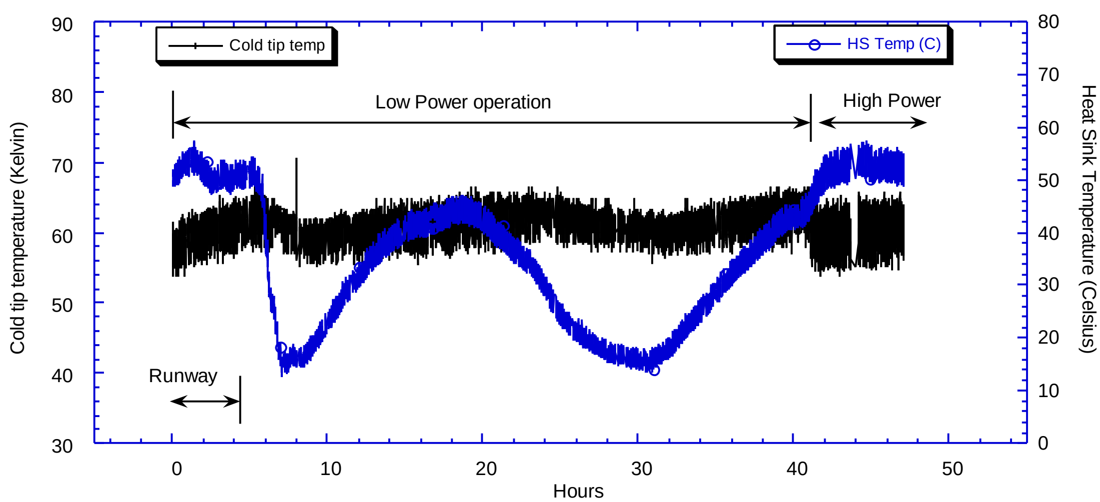


Figure 4: Heat sink and cold tip temperatures . Cold tip with a 2 watt simulated

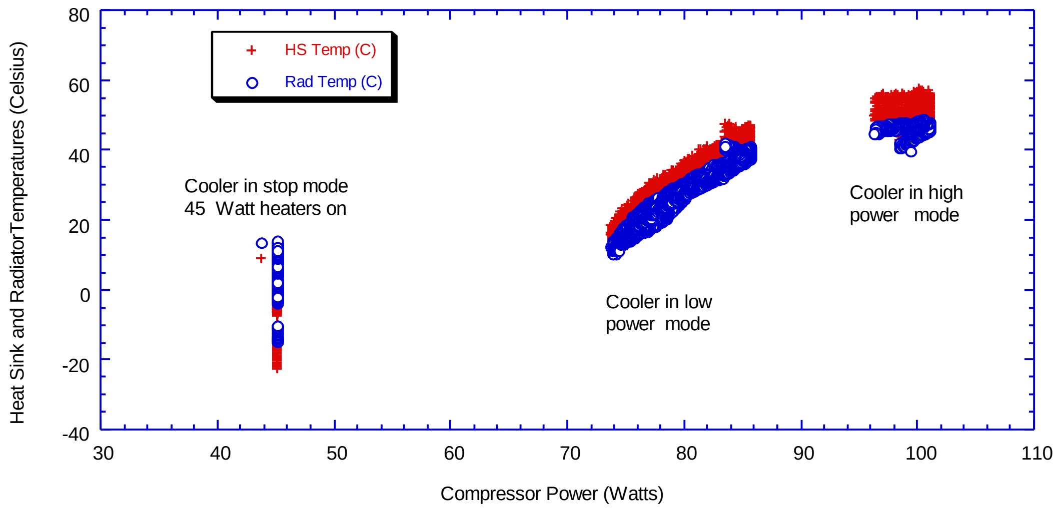
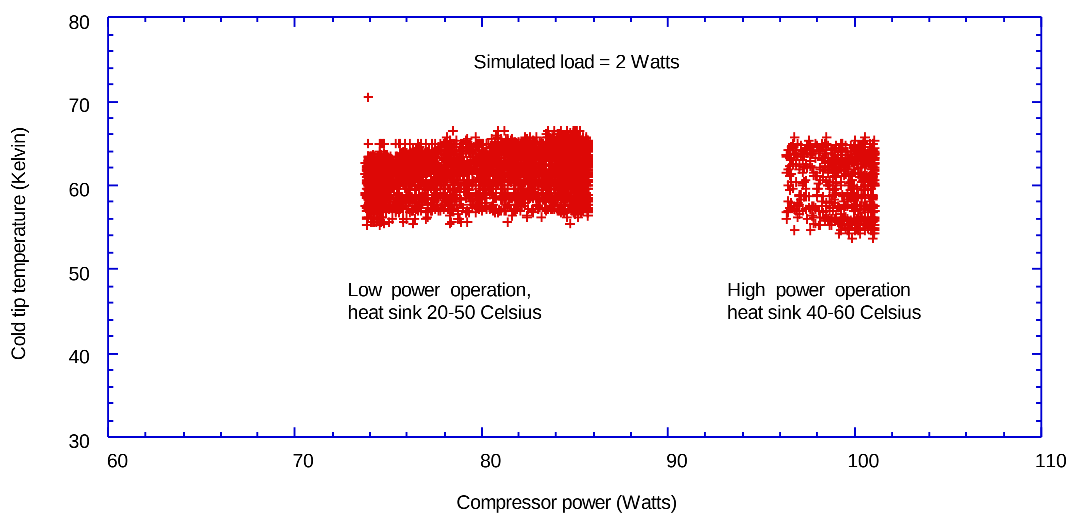


Figure 5: Heat sink and Radiator performance at low power, high power, and with 45 watt load.



.**Figure 6**: Cold tip temperature measurement for both high power and low power modes

Figure 5 includes only data acquired at altitude. The three levels are low power mode, high power mode, and a constant 45 watt load simulating the compressor.

Cryocooler cold tip temperature during the second flight is presented in Figure 6. Note that the heat sink temperature was considerably higher in the high power mode than that in the low power mode. The cold tip temperature performance shown in Figure 6 is very close to what is measured in the NASA cryogenics branch thermal vacuum chamber with tests performed on another M77B Sunpower cryocooler. Two thermal vacuum chamber test results were 60 Kelvin cold tip temperature with 100 watts compressor power, 30 degree celsius heat sink, and a 70 Kelvin cold tip temperature with 60 watts compressor power , and 30 degree celsius heat sink. Both tests conducted with a 2 watt simulated load on the cold tip.

CONCLUSIONS

The sequence of commands established for the cryocooler during the flight was to run first at low power and low load, then high power and low load, then high power and high load, and finally low power and high load. Data was collected for low power and low load, and high power and low load only. While most of the desired thermodynamic data was obtained, a complete thermodynamic load line was not possible since the cryocooler stopped running prior to the command to high load.

A fluctuation of the gain control electronics with temperature was discovered and has been subsequently investigated. An alternative design has been implemented for use on possible future balloon missions that eliminates the gain control temperature sensitivity.

Sufficient data was collected to characterize the radiator effectiveness at removing heat from the cooler. The cryocooler was mounted off center on the radiator, which probably resulted in some loss of cooling effectiveness. Other methods to improve radiator effectivness are being investigated.

The flight revealed a need to enclose electronics unit, and make it accessible, without removing the cooler and radiator from the gondola.

No electromagnetic incompatibility was found to exist while the cryocooler was running.

Prior to launch, all systems were running on a generator and not batteries; this ensures that the batteries are not drained. Moments before launch the 28 V dc supplied to cryocooler is hot switched over to batteries, and a significant voltage transient was measured which could cause damage to the electronics. Design modifications have been investigated to protect the cooler electronics from this voltage transient.

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